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Evidence for $\nu_\mu \to \nu_\tau$ oscillations in the OPERA experiment

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Summary. — The OPERA experiment is designed to search for $\nu_\mu \to \nu_\tau$ oscillations in appearance mode by seeing both the production and decay vertices of the τ lepton. The detector, located in the underground Gran Sasso laboratory, is based on a hybrid technique using nuclear emulsions complemented by electronic detectors. Emulsions are used as micrometric tracking devices in the target region. The experiment has been taking data for five years, since 2008, with the CERN Neutrino to Gran Sasso beam (CNGS) over a baseline of 730 km. From the analysis of a subsample of data, three ν_τ candidates have been found. We describe the candidates and discuss the significance of the result in terms of a $\nu_\mu \to \nu_\tau$ oscillation signal.

PACS `14.60.Pq` – Neutrino mass and mixing.
PACS `14.60.St` – Non-standard-model neutrinos, right-handed neutrinos, etc..

1. – The OPERA experiment

Neutrino mass eigenstates do not coincide with flavor eigenstates as it happens also in the quark sector. Since their mass eigenstates are not degenerate, flavor transitions known as neutrino oscillations appear. Neutrino oscillations were postulated nearly 50 years ago [1, 2] while they were experimentally proved only in 1998 when the Super-Kamiokande experiment provided the evidence for neutrino oscillations in the atmospheric neutrino sector [3]. This experiment showed that ν_μ were disappearing and they were not oscillating to ν_e. Experimental evidence for ν_μ disappearance was later given also with artificial beams [4,5] and in the same years it was established that the $\nu_\mu \to \nu_e$ transition could not explain the ν_μ disappearance [6]. Only recently the amplitude of the $\nu_\mu \to \nu_e$ transition, governed by the θ_{13} angle, was measured [7] while the first evidence for a non-vanishinng θ_{13} was provided by reactor experiments [8, 9]. The only missing tile in this three flavor oscillation scenario is the evidence for the appearance of ν_τ's in a ν_μ beam.

This is the motivation of the OPERA experiment [10] designed to prove the $\nu_\mu \to \nu_\tau$ transition in appearance mode by seeing the τ lepton produced in a charged-current ν_τ

interaction. To accomplish this task, several ingredients are mandatory: a high energy neutrino beam, a long baseline, a high-mass detector (kton scale) and a micrometric resolution. The CNGS beam was designed at CERN to produce 17 GeV ν_μ delivered at Gran Sasso, 730 km away. The beam contains a small (below 1%) contamination of electron neutrinos while the contamination of ν_τ is totally negligible. The OPERA detector is located in the underground Gran Sasso laboratory in Italy and it is based on the nucler emulsion technology. The target region of about 1.2 kton has a modular structure with target units, called bricks, made of a sandwich structure alternating lead plates acting as the neutrino target and nuclear emulsion films used as micrometric tracking devices. The target region is made of brick walls interleaved with scintillator trackers that provide the time stamp of the event and predict bricks where neutrinos interact. The target is complemented by magnetic spectrometers deputed to the measurement of the muon charge and momentum. The iron magnets are instrumented with RPC's.

2. – Data analysis and ν_τ candidates

The CNGS has been operating for five years, since 2008 till December 2012, delivering a total of 18.0×10^{19} pot (protons on target) corresponding to about 19000 neutrino interactions collected in the target. On average about 18 interactions were collected every day. The brick where the interaction is predicted by the analysis of the electronic detector data is extracted from the target by a brick manipulator system and its films are analysed. Interface emulsion films are placed in between the brick and the scintillating target trackers. If their analysis confirms the presence of a neutrino interaction in the brick, emulsion films in the brick are developed and scanned in the different laboratories of the Collaboration. The emulsion film analysis provides the tridimensional reconstruction with micrometric accuracy of neutrino interactions and of possible secondary vertices due to short living particle decays.

Although the primary goal of the OPERA experiment is the ν_τ detection, the detector shows a very high purity and good efficiency in the detection of ν_e interactions. In fact, the micrometric accuracy allows a very high discrimination between electrons and π^0's (through electron pairs produced by γ's) such that the contamination of ν_μ neutral-current interactions in ν_e is less than 1%. A search for electron neutrinos was performed with the data of 2008 and 2009 runs and 19 ν_e candidates were collected. This result is consistent with the expectation of 19.8 ± 2.8 events in absence of oscillations, given the fact that the beam is not optimised for the ν_e appearance. The ν_e search has been used to constrain the parameter space of mixing angle and Δm^2 for non-standard oscillations, setting the upper limit at 90% C.L. on the mixing angle, $\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ for large ($> 0.1\,\mathrm{eV}^2$) Δm^2_{new} values [11].

The data collected in the first two years (2008 and 2009) were fully analysed. The strategy initially adopted for the ν_τ search did not foresee any kinematical cut, in order to avoid any bias before a complete understanding of the data was proven. From the analysis of these data, one event collected in 2009 showed the kink topology, *i.e.* an angular deflection typical of decays of a charged particle into a single charged daughter. After the full reconstruction of the event and its kinematical analysis, it became the first ν_τ candidate [12]. The event is interpretable as a τ lepton produced in a primary neutrino interaction and decaying into the $\tau \to \rho\nu_\tau$ channel with subsequent $\rho \to \pi^0\pi$ decay. The π^0 invariant mass was reconstructed from the measured energy of the 2 γ's detected in the emulsions while an invariant mass consistent with the ρ particle was measured from π and π^0 momenta.

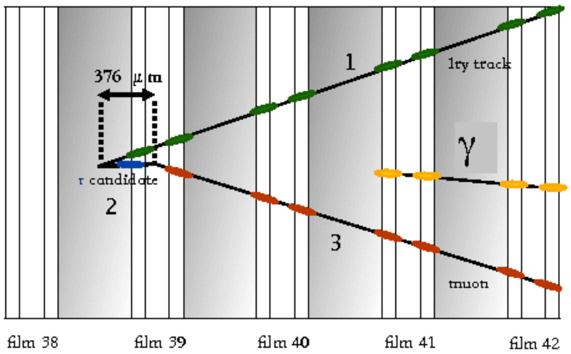

Fig. 1. – Schematic drawing of the neutrino interaction and tau decay vertices. Lead plates are dark while emulsion films are white. The neutrino is coming from the left.

After the achievement of a satisfactory description of the data provided by electronic detectors [13], a muon momentum cut at $15\,\mathrm{GeV}/c$ was applied in order to discard high energy muons coming mostly from charged-current ν_μ interactions. The analysis of 2010 and 2011 run events was also prioritising events without a muon in the final state, where the τ content is larger ($\tau \to \mu$ branching ratio is about 17%). From the analysis of this data sample, a second ν_τ candidate was found [14]. It was collected in the 2011 run data and it showed the three prong decay topology. After its kinematical analysis, it turned out to be consistent with the $\tau \to \pi\pi\pi\nu_\tau$ decay channel. The observation of this candidate was also reported at the Neutrino 2012 Conference.

After this Conference, the Collaboration extended the analysis also to the muonic channel. From the analysis of the 2012 run, an event was found in the muonic channel with the kink decay topology [15, 16]. At the primary vertex two charged particles were reconstructed, one of them showing a kink topology after travelling $376\,\mu$m. The charged daughter is the particle identified as a muon by the electronic detector. An electromagnetic shower initiated by a γ was detected in the brick. From the analysis of the γ direction, it turned out to be associated to the primary vertex, being produced by a primary π^0. The schematic view of the neutrino interaction vertex and the subsequent τ candidate decay is reported in fig. 1. The decay happens to be in the emulsion film. This feature allows to see in the same emulsion film both the parent particle and its daughter. The muon momentum measured by range is $2.8 \pm 0.2\,\mathrm{GeV}/c$ while the kink angle is as large as 245 mrad, giving a transverse momentum of $(690 \pm 50)\,\mathrm{MeV}/c$. In the plane orthogonal to beam, the angle ϕ between the τ candidate and the hadronic system at the primary vertex is $(155 \pm 15)^\circ$. This angle is expected to tend to 180° when all the activity is detected, being the τ almost back to back to the hadronic system except for the Fermi motion.

The most downstream part of the muon trajectory falls in the magnetised region and it was therefore possible to estimate the muon charge. The left plot of fig. 2 shows the event display with the muon hits all along its trajectory, from the target tracker to the muon spectrometer. The right plot shows the last part of the muon trajectory and the fit of its electronic detector hits: a straight line was used in the target region and a parabola in the magnetised region. The second coefficient of the parabola estimated by the fit provides its curvature and therefore its charge. This coefficient is negative, being different from zero with 5.6σ and therefore the muon charge is negative with a large significance, ruling

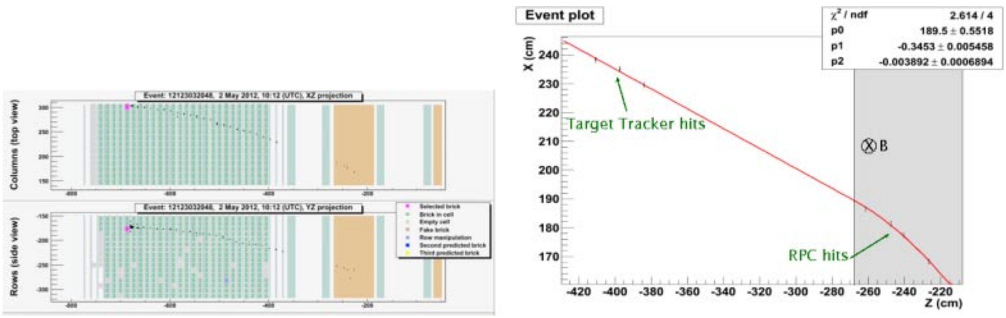

Fig. 2. – Left: muon hits in the electronic detector as seen by the event display. The unit of the scale is cm. Right: fit of the muon hits with a straight line in the target region and with a parabola in the magnetised region. The curvature towards the bottom provides the indication of the negative charge with 5.6σ significance.

out the charmed particle decay hypothesis. The other charged particle at the primary vertex has been followed downstream up to the stopping point detected after having crossed about 4 cm of lead. The correlation between its momentum and range identifies this particle as a hadron. All the features, both topological and kinematical, of this event makes it a candidate of a ν_τ interaction with subsequent $\tau^- \to \mu^-$ decay.

3. – Results

The main background source for the ν_τ search is charmed hadron production in ν_μ charged-current interactions when the muon is undetected. The muon identification at the level of the electronic detector is complemented by a procedure that exploits the emulsion information. All the tracks at the primary vertex are followed down along their trajectory until they stop or interact. The interaction is a clear evidence of the hadronic nature of the particle while, when the track stops, the momentum correlation efficiently separate muons and hadrons. This procedure is being further optimised. The present level of charm background in the analysed sample amounts to 0.145 ± 0.020 events as reported in table I. Minor background sources are coming from hadronic interactions, mimiking a τ signal when no nuclear break-up is detected, and large angle muon scattering affecting only the muonic decay channel. These processes are quite rare and their yield is reported in table I. When summed up to the charm background, the total yield in the analysed sample is 0.184 ± 0.025 events.

Table I. – *Background sources in the ν_τ search and their yield in the different channels.*

Decay channel	Background	Charm	Had. interactions	μ scattering
$\tau \to h$	0.027	0.011	0.016	
$\tau \to 3h$	0.12	0.11	0.002	
$\tau \to e$	0.020	0.020		
$\tau \to \mu$	0.020	0.004		0.016
Overall	0.184 ± 0.025	0.145 ± 0.020	0.018 ± 0.006	0.02 ± 0.01

Given the background yield, the three observed events can be turned into a significance of the observation of $\nu_\mu \to \nu_\tau$ oscillations. Four random integers n_i are extracted according to the Poisson distributions of the background in the four τ decay channels, respectively. The p-values, p_i, are then calculated as the Poissonian probability to observe at least n_i events in the i-th channel for each pseudo-experiment and the estimator p^* used is their product, *i.e.* $p^* = p_h p_{3h} p_\mu p_e$. The fraction of pseudo-experiments with $p^* < p_{obs}$ is 2.9×10^{-4} providing a significance of 3.4σ for the non-null observation.

4. – Conclusions

The OPERA experiment has carried out the analysis of a subsample of its data set integrated along five years of data taking in the CNGS beam, since 2008 until December 2012. From this analysis, three ν_τ candidates have been found with an expected background of 0.184 ± 0.025 events. The background estimate is conservative and lever arms to further increase the muon identification capabilities are being explored. This result provides the first evidence for $\nu_\mu \to \nu_\tau$ oscillations in appearance mode, being passed the level of 3σ in the observation of the process. The analysis of the data is still in progress and will last for about two more years with the goal of achieving the observation at the 4σ level.

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